



Zhu, X., Doufexi, A., & Koçak, T. (2011). A performance evaluation of 60 GHz MIMO systems for IEEE 802.11ad WPANs. In *IEEE 22nd International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC), 2011* (pp. 950 - 954). Institute of Electrical and Electronics Engineers (IEEE).
<https://doi.org/10.1109/PIMRC.2011.6140109>

Peer reviewed version

Link to published version (if available):
[10.1109/PIMRC.2011.6140109](https://doi.org/10.1109/PIMRC.2011.6140109)

[Link to publication record in Explore Bristol Research](#)
PDF-document

University of Bristol - Explore Bristol Research

General rights

This document is made available in accordance with publisher policies. Please cite only the published version using the reference above. Full terms of use are available:
<http://www.bristol.ac.uk/red/research-policy/pure/user-guides/ebr-terms/>

A Performance Evaluation of 60 GHz MIMO Systems for IEEE 802.11ad WPANs

Xiaoyi Zhu^{*}, Angela Doufexi^{*}, and Taskin Kocak[†]

^{*}Department of Electrical and Electronic Engineering
University of Bristol, Bristol, United Kingdom
{X.Zhu, A.Doufexi}@bristol.ac.uk

[†]Department of Computer Engineering
Bahcesehir University, Istanbul, Turkey
Taskin.Kocak@bahcesehir.edu.tr

Abstract— The IEEE 802.11ad task group has published its first draft to cope with the characteristics in 60 GHz millimeter-wave (mmWave) wireless communications. In this paper, three different 2×2 multiple-input multiple-output (MIMO) techniques are considered to enhance the performance of 60 GHz wireless personal networks (WPANs). Packet Error Rate (PER) and link throughput performance are simulated under different channel conditions. In addition, the system throughput over operation range is presented in the paper. Results show that significant enhancements in both coverage and capacity can be achieved by employing space-time block codes (STBC), spatial multiplexing (SM) and three different configurations of beamforming.

Keywords- WPAN; 60 GHz; IEEE 802.11ad; OFDM; MIMO

I. INTRODUCTION

The wireless local and personal communications have been experienced increasing interest with the tremendous growth in multimedia applications in recent years. The successful 2.4/5 GHz wireless systems have already increased the data rate to 600 Mbps with multiple-input multiple-output (MIMO) techniques. However, with the development of CMOS design and the availability of the 60 GHz unlicensed millimeter-wave (mmWave) band, it is possible to deliver even higher quality multimedia and data services. To accommodate the characteristics of the mmWave, the IEEE 802.11ad task group was formed to amend the existing standard on both physical (PHY) and medium access control (MAC) layers within the 57-66 GHz band [1]. The orthogonal frequency division multiplexing (OFDM) and single carrier (SC) transmission are specified in the standard. The SC mode is used for control information and low complexity transceivers, while the OFDM mode is designed for delivering high performance applications.

MIMO techniques have been studied extensively in the last decade, and in general, they can be classified into three types. One of the techniques is space-time block coding (STBC), which aims to improve the power efficiency by maximizing spatial diversity. The advantage of STBC is it enables the use of linear decoding at the receiver, and with OFDM, it can be easily implemented. Another technique is spatial multiplexing (SM), which increases the spectral efficiency by transmitting parallel data streams without the need of extra bandwidth. A higher throughput can be achieved by SM and the process does not introduce any coding redundancy. Beamforming is the third type of multiple antenna technique, and the objective is to utilize the directivity of the signal transmission and reception.

Compared to STBC and SM, beamforming only needs to utilize one spatial channel among a multiple of parallel channels. In OFDM system, beamforming can be carried out by three generic types, namely, subcarrier-wise beamforming, symbol-wise beamforming, and hybrid beamforming [2]. The first type performs beamforming in the frequency domain and the second type carries out in the time domain. The hybrid beamforming, which employs symbol-wise beamforming at the transmitter and subcarrier-wise beamforming at the receiver, compromises the complexity and performance.

The rest of this paper is organized as follows. The PHY and channel models of IEEE 802.11ad WPANs are presented in Section II. The OFDM based MIMO models are described in Section III. In Section IV, the packet error rate (PER) performance of STBC, SM and three different beamforming schemes are simulated using our IEEE 802.11ad PHY simulator. The link throughput and operation range results are also investigated. Section V concludes the paper.

II. WPANs PHY AND CHANNEL MODELS

In IEEE 802.11ad, the large spectrum around 60 GHz is equally divided into four channels. In this study, an OFDM system with 2.16 GHz bandwidth is considered to combat frequency selective fading. The OFDM is implemented by means of an inverse FFT, and a total number of 512 subcarriers are transmitted in parallel in the form of one OFDM symbol. In order to eliminate inter symbol interference (ISI), a length of 128 cyclic prefix is added to each symbol. The key parameters used for the simulation of the MIMO-OFDM PHY in this paper are shown in Table I.

TABLE I. PARAMETERS FOR OFDM SYSTEMS IN IEEE 802.11AD

Parameter	Value
Sampling frequency (MHz)	2640
Number of subcarriers	512
Number of data subcarriers	336
Number of pilot subcarriers	16
Subcarrier frequency spacing (MHz)	5.156
Sample duration (ns)	0.38
IFFT and FFT period (ns)	194
OFDM symbol duration (ns)	242

Let \mathbf{y}_m be the received decision baseband signal for the m th subcarrier, which can be expressed as

$$\mathbf{y}_m = \tilde{\mathbf{H}}_m \mathbf{x}_m + \mathbf{n}_m, \quad m = 1, \dots, N \quad (1)$$

where \mathbf{x}_m is the transmitted data symbol, \mathbf{n}_m is the Gaussian noise vector with zero mean and variance σ^2 , N is number of subcarriers, and $\tilde{\mathbf{H}}_m$ represents the frequency response of the equivalent channel matrix for the m th subcarrier.

Based on the clustering phenomenon in both the temporal and spatial domains, a statistic channel model from a combination of measurements and ray-tracing was proposed for the 60 GHz WPANs [3]. We consider a 1-D uniform linear array consisting of M_t and M_r antenna elements at the transmitter and the receiver respectively. The antenna element spacing is half wavelength λ . The channels are generated with isotropic radiators in both line-of-sight (LOS) and non-line-of-sight (NLOS) cases. To evaluate the performance of STBC and SM in IEEE 802.11ad, different degrees of channel correlation are considered. We assume the average channel matrix value across all channel realizations are 0.1 (low), 0.5 (medium) and 0.9 (high) respectively. It is assumed that the communication channel remains constant during an OFDM data packet transmission. The 60 GHz average path loss (PL) model considering shadow fading can be modeled as [3]:

$$PL(\text{dB}) = A + 20 \log_{10}(f) + 10n \log_{10}(D) \quad (2)$$

where for LOS scenario $A = 32.5$ dB, $n = 2.0$, and for NLOS scenario $A = 51.5$ dB, $n = 0.6$, f is the carrier frequency in GHz, and D is the distance between the transceivers in meter.

III. OFDM BASED MIMO MODEL

Fig. 1 describes a generic MIMO-OFDM block diagram of the transmitter for IEEE 802.11ad WPANs. It consists of M_t IFFT blocks before which the incoming bits are scrambled, encoded with LDPC, interleaved, constellation mapped, and MIMO processed. In this paper, MIMO systems with two transmit and two receive antennas ($M_t = M_r = 2$) are considered as a means of enhancing the performance and throughput of WPANs. The modulation and coding schemes (MCSs) we considered in this paper are listed in Table II.

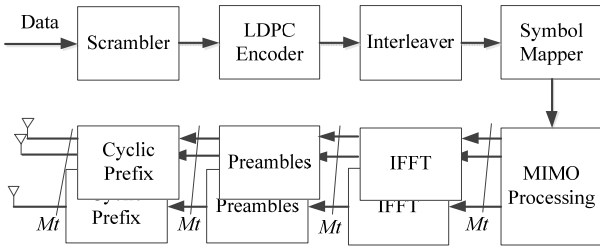


Figure 1: Block diagram of MIMO-OFDM transmitter

A. Space-Time Block Coding (STBC)

In [4] Alamouti proposed a simple transmit diversity scheme to form STBC. These codes achieve the same diversity advantage as maximal ratio receiver combining. The transmit diversity can be easily applied to OFDM in order to achieve a diversity gain over frequency selective fading channels. For a 2×2 STBC architecture, the scheme uses a transmission matrix $[x_1, -x_2^*; x_2, x_1^*]$, where x_1 and x_2 are two consecutive OFDM symbols.

TABLE II. MODULATION AND CODING SCHEMES CONSIDERED

Modulation & Coding Rate	Coded Bits/Symbol	Data Bits/Symbol	Data Rate (Mbps)	SM Data Rate (Mbps)
QPSK 1/2	672	336	1386.00	2772.00
QPSK 5/8	672	420	1732.50	3465.00
QPSK 3/4	672	504	2079.00	4158.00
16-QAM 1/2	1344	672	2772.00	5544.00
16-QAM 5/8	1344	840	3465.00	6930.00
16-QAM 3/4	1344	1008	4158.00	8316.00
16-QAM 13/16	1344	1092	4504.50	9009.00
64-QAM 5/8	2016	1260	5197.50	10395.00
64-QAM 3/4	2016	1512	6237.00	12474.00
64-QAM 13/16	2016	1638	6756.75	13513.50

B. Spatial Multiplexing (SM)

Typically, SM scheme is used for increasing the peak data rate by transmitting separate data streams from each antenna. A 2×2 SM system can double the peak data rate. In 60 GHz WPANs, since the highest MCS mode has already reached to 6.7 Gbps, the data rate is no longer the major concern compared to other wireless systems operating at lower frequencies. We employ this scheme in order to increase the reliability and throughput of lower MCS modes. This comes at the expense of sacrificing diversity gain, and hence a higher signal-to-noise-ratio (SNR) is required. In MIMO detection, in order to obtain a good performance with reasonable complexity, a linear Minimum Mean Squared Error (MMSE) receiver is adopted. For both STBC and SM, an FFT/IFFT processor is required for each antenna element.

C. Beamforming

Beamforming uses knowledge of the channel state information (CSI) to create a set of weight vectors. The vectors are used on the data before transmitting to the channel, so that they can be extracted without interference at the receiver. Recall equation (1), we have

$$\tilde{\mathbf{H}}_m = \mathbf{c}^H \mathbf{H}_m \mathbf{w}, \quad m = 1, \dots, N \quad (3)$$

where \mathbf{H}_m represents the response of the MIMO channel for the m th subcarrier, and \mathbf{w} and \mathbf{c} are the transmitter and the receiver beam steering vector respectively. In this work, we use the effective SNR as the criterion to choose the optimal \mathbf{w} and \mathbf{c} . The effective SNR defined as the average SNR across all subcarriers can be computed as [5]

$$\gamma_{eff} = -\beta \ln \left(\frac{1}{N} \sum_{m=1}^N \exp(-\gamma_m/\beta) \right) \quad (4)$$

where γ_m is the symbol SNR experienced on the m th subcarrier, β is a parameter dependent on the coding rate, the modulation and the information block size. The SNR of the m th subcarrier after normalization can be calculated as follows [2]

$$\gamma_m = \frac{E[|\mathbf{c}^H \mathbf{H}_m \mathbf{w} x_m|^2]}{E[|\mathbf{n}_m|^2]} = \frac{|\mathbf{c}^H \mathbf{H}_m \mathbf{w}|^2}{M_t M_r \sigma^2} \quad (5)$$

When implementing the beamforming technique to an OFDM system, three different configurations are considered in this work. Subcarrier-beamforming is the optimal solution [6], which maximizes the average received SNR on each subcarrier: $\{c, w\} \in \max_{c, w} \gamma_m$. This maximization can be achieved by finding the first entry of singular value

decomposition (SVD) of the channel matrix. As shown in Fig. 2, subcarrier-wise beamforming requires one FFT/IFFT processor per antenna. In addition, estimated channel matrix must be sent back to the transmitter, and the weight computation need a SVD processor per subcarrier.

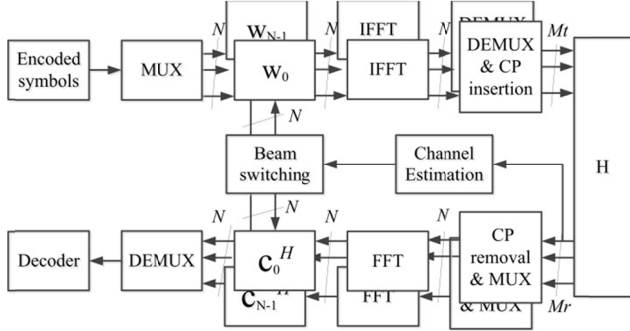


Figure 2: Block diagram of subcarrier-wise beamforming

Despite the superior performance, in practice, this type of beamforming is not employed because of the high complexity. The complexity can be reduced by performing beamforming in the time domain as shown in Fig. 3. Symbol-wise beamforming [6] requires only one FFT processor at each terminal, and each subcarrier applies the same weight vector. Compared to subcarrier-wise beamforming, symbol-wise beamforming will introduce a performance loss because only the maximum effective SNR for overall subcarriers can be satisfied. [2] proposed a hybrid beamforming technique, in which the symbol-wise beamforming is employed at the transmitter to minimize the complexity, and the receiver is configured with subcarrier-wise beamforming to optimize the performance. The structure is shown in Fig. 4.

However, in practice, obtaining CSI is computationally intensive, and in order to avoid these calculations, a set of pre-defined beam codebook is used for rapid processing in 60 GHz systems [7]. As defined in [8], the beam codebook is created with four orthogonal shifts per antenna element without amplitude adjustment. It is determined by both the number of antenna elements, and the desired number of beams. Then, the problem for symbol-wise beamforming becomes to find the best pair of codebook (CB): $\{c, w\} \in \max_{c, w \in CB} \gamma_{eff}$. While for hybrid beamforming, we only need to choose the optimal transmitter vector w from the codebook: $\{c, w\} \in \max_{w \in CB} \gamma_{eff}$, and the optimal receiver beam steering vector $c_{m,opt}$ can be obtained from w by using Schwartz's inequality.

IV. NUMERICAL RESULTS

A. Link Level Simulation Results

In this section, we use our IEEE 802.11ad PHY MATLAB simulator to present the PER performance of single antenna system (SISO) and MIMO schemes we described in the previous section. The packet size is 1 KB in all scenarios.

Fig. 5 presents the SISO PER performance of all the modes versus the average SNR for the LOS channel. It can be seen that in general higher data rate requires higher SNR to maintain a certain PER. The system cannot provide any service when the SNR is below 1 dB in such a scenario. Given the PER transmission target of 1%, the system will be at the highest

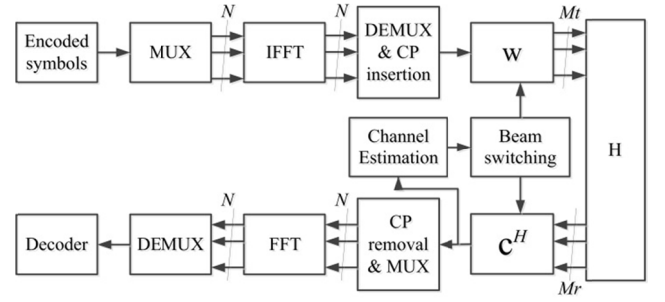


Figure 3: Block diagram of symbol-wise beamforming

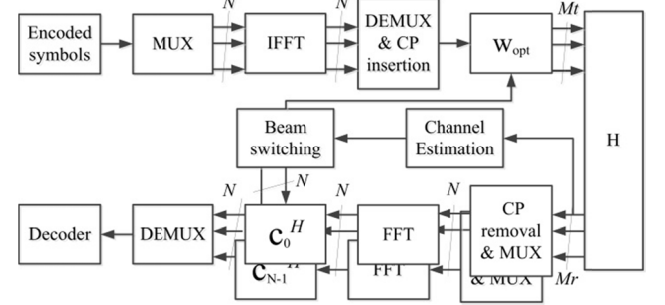


Figure 4: Block diagram of hybrid beamforming

MCS at approximately 22 dB. For the NLOS scenario, the PER shows similar trends, but in order to maintain the same PER, the system needs 4-5 dB higher SNR. In addition, larger packet size results in a higher SNR to maintain PER performance.

Fig. 6 compares the MCS QPSK 1/2 PER performance for the SISO and different MIMO 2x2 schemes in LOS. For both STBC and SM systems, we assume the channels are highly correlated. Three different beamforming techniques are also considered. It is shown that to achieve a PER at 1%, STBC gives around 7 dB gain over the SISO system, while the three beamforming schemes offer about 5 dB gain. Although the PER performance difference is not distinct in LOS, it still can be seen that the subcarrier-wise beamforming is shown to be the best, the hybrid beamforming is the next and the symbol-wise beamforming is the worst. However, when the correlation of the channel is very high, e.g. 0.9, 2x2 SM is almost unusable, even at low MCS.

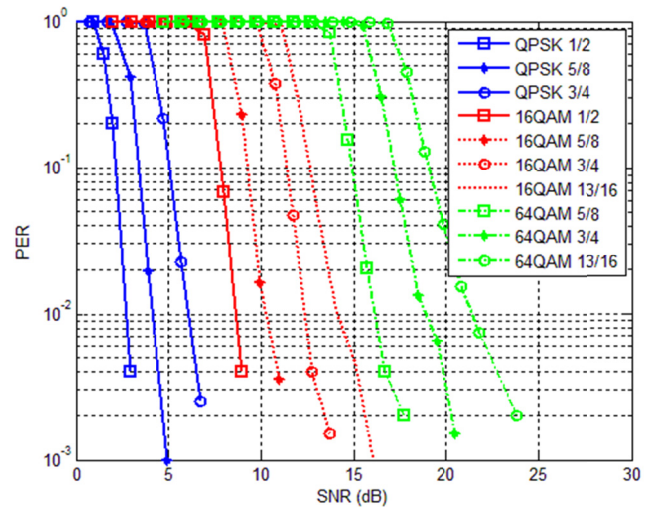


Figure 5: PER performance of the SISO system with LOS

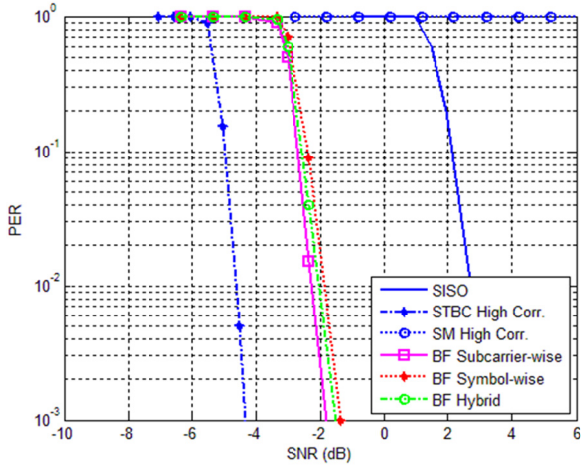


Figure 6: PER performance comparison of MIMO schemes with LOS

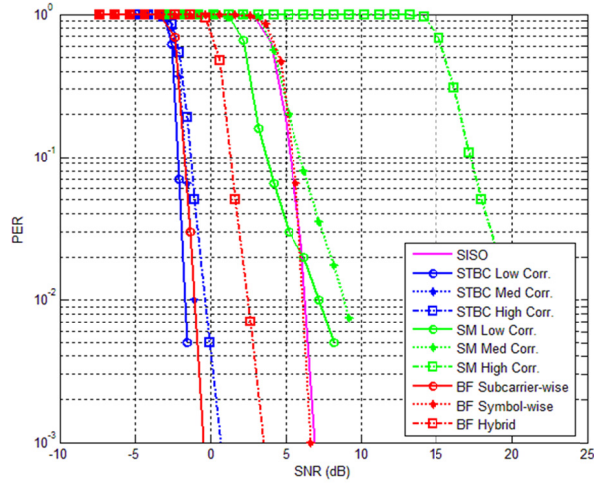


Figure 7: PER performance comparison of MIMO schemes with NLOS

In Fig. 7, the MCS QPSK 1/2 PER performance for the SISO and all MIMO 2×2 schemes are presented for the NLOS case. For STBC and SM, different levels of channel correlation are considered. It can be seen that the performance of STBC and SM varies depending on the correlation factors. Generally, a lower correlation provides a better PER performance. We can observe that STBC offers a significant PER gain of about 7-8.5 dB compared to SISO. However, to achieve a PER target of 1%, the SM requires higher SNR than SISO. Nevertheless, in the case of 2×2 SM, data rate can be almost doubled due to the simultaneous transmission of two parallel data streams. Since the MIMO 2×2 SM with high correlation coefficient introduces too much PER, we will not consider this scheme in the following analysis. In addition, it is also shown that the subcarrier-wise beamforming gives about 7 dB gain over the SISO system, which is almost equivalent to STBC. However, the symbol-wise beamforming could provide very little gain in NLOS. It is worth mentioning that about 4 dB gain can be achieved by hybrid beamforming, which distinctly improves the performance over symbol-wise beamforming.

B. Throughput Performance Analysis

In order to enable the system to adapt the transmission mode to the link quality, the PHY modes with different MCSs

are selected by a link adaptation scheme. The achievable link throughput is given by: $Throughput = R(1 - PER)$, where R and PER are the peak data rate and packet error rate for a specific mode respectively. As shown in Fig. 8 and Fig. 9, the throughput envelop is the ideal adaptive MCS based on the optimum MCS switching point. It can be seen in Fig. 8 that STBC and the three beamforming schemes do not improve the peak error-free throughput, but at a certain SNR, MIMO systems outperform the SISO system. The beamforming schemes achieve about 5-6 dB gain in comparison to the SISO system. In addition, STBC could give extra 2 dB SNR gain. However, STBC requires one FFT/IFFT processor per antenna, which is not the case for symbol-wise beamforming.

In the NLOS scenario, for the following reasons: (1) the throughput of STBC with different levels of correlation is very similar; (2) the performance of subcarrier-wise beamforming is very close to STBC, we only plot medium correlated STBC and SM, as well as symbol-wise beamforming and hybrid beamforming, to compare the throughput. As shown in Fig. 9, to maintain the same throughput, STBC and hybrid beamforming provide approximately 2-6 dB gain compared to SISO. Even more gain can be achieved for very high throughput (>3500 Mbps). The symbol-wise beamforming has better performance beyond 16 dB, so high MCS modes will

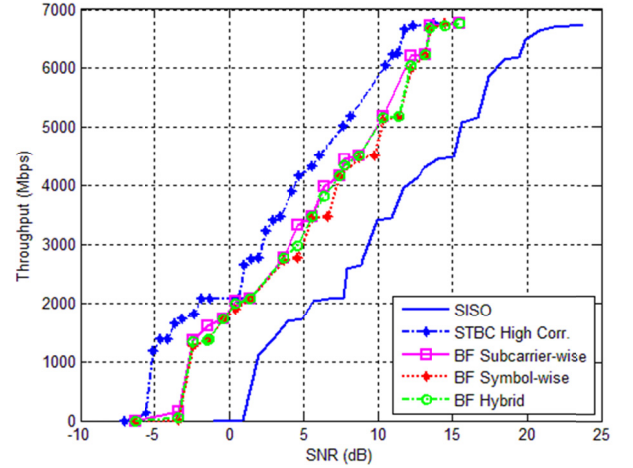


Figure 8: Link throughput with LOS

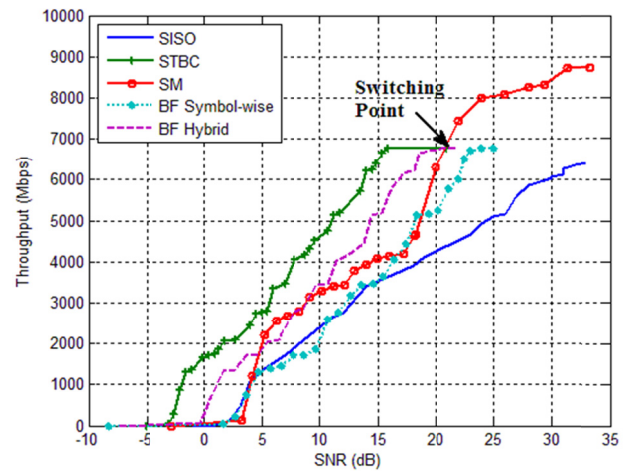


Figure 9: Link throughput with NLOS

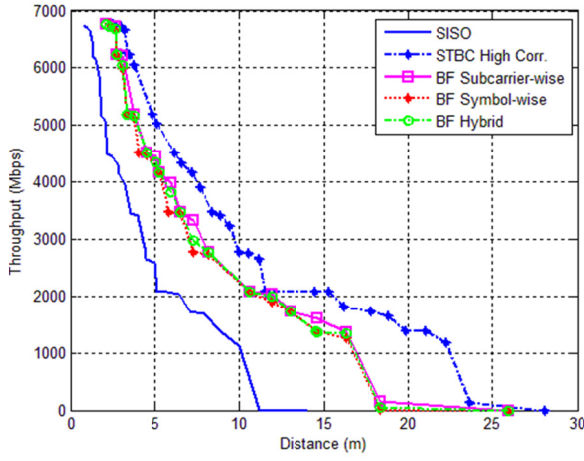


Figure 10: Operation range with LOS

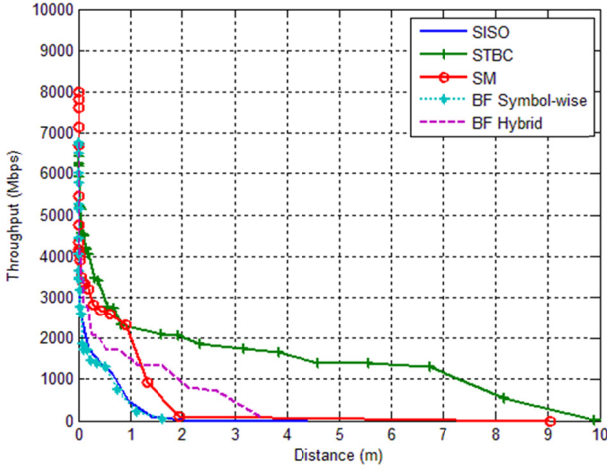


Figure 11: Operation range with NLOS

benefit from this scheme. The performance of SM is worse than STBC and hybrid beamforming, but after the switching point at about 21 dB, the increased error-free data rate makes SM the best choice. This value will increase with the increasing of spatial correlation.

C. Operation Range Analysis

In this section, we study the MIMO techniques impact on the operation range. The achievable operation range is derived from the link budget which can be described as:

$$P_T - PL \geq kTB + NF + \text{ReceiverSNR} \quad (6)$$

where P_T is the maximum transmit power (10dBm) [1], k is Boltzmann's constant, T is the room temperature (290K), B is the bandwidth, NF represents the noise figure (10dB) of such devices [1], and ReceiverSNR is the SNR required for the demodulation. Fig. 10 and Fig. 11 illustrate the maximum data rate that can be achieved over distance, based on the average path loss model in (2) and the results of link throughput.

With the link adaption scheme applied, the system can operate at its maximum throughput when the devices are close, and adaptively switch to the lower speed when a device moves further away. It can be observed that the maximum tolerant distance for the SISO in LOS is about 12m, but in order to

guarantee high throughput applications (>3000 Mbps), the transceivers distance should be within 4m. The beamforming schemes extend the operation range to about 18m, and almost increase 50% the tolerant distance to guarantee the high data rate. STBC extends the effective transmission range up to 25m. In the case of NLOS, the SISO system could not provide service beyond 1m, but the hybrid beamforming extends the achievable operating range to about 3.5m. STBC and SM could provide very high data rate above 2000 Mbps within 2m and 1m respectively. The throughput of SM quickly drops within 2m range; however, STBC is still possible to provide service up to 10m.

V. CONCLUSIONS

This paper has presented a performance evaluation of three types of popular MIMO techniques over the OFDM based 60 GHz millimeter-wave WPAN. PER performance results for SISO and 2×2 MIMO were presented under the typical channel models developed by IEEE 802.11ad. The adaptive link throughput are presented based on the simulated PER results. The achievable operation range is also investigated using the 60 GHz path loss model. The results demonstrate that STBC produces the best performance due to its robustness in all channel conditions. The 2×2 SM doubles the error-free data rate for NLOS medium correlation channels. It is still possible to deliver even higher data rate more than 7000 Mbps, but this is not very crucial. All three beamforming schemes increase the system performance significantly in LOS. When there is no LOS, hybrid beamforming provide considerable improvements while maintaining reasonable hardware complexity.

ACKNOWLEDGMENT

The authors would like to express their sincere appreciation to Blu-Wireless Technology for technical input, and also want to acknowledge the financial support provided by ClearSpeed Technology Ltd and Great Western Research (GWR).

REFERENCES

- [1] IEEE 802.11 Task Group AD, "PHY/MAC Complete Proposal Specification", IEEE 802.11-10/0433r2, May 2010.
- [2] S. Yoon, T. Jeon and W. Lee, "Hybrid Beam-forming and Beam-switch for OFDM Based Wireless Personal Area Network", *IEEE Journal on Selected Areas in Communications*, Vol. 27, Issue 8, pp. 1425-1432, October 2009.
- [3] A. Maltsev, V. Erceg, E. Perahia, *et.al.*, "Channel Models for 60 GHz WLAN Systems", IEEE 802.11-09-0334-08-00ad, May 2010.
- [4] M. Alamouti, "A Simple Transmit Diversity Technique for Wireless Communications", *IEEE Journal on Selected Areas in Communications*, Vol. 16, Issue. 8, pp. 1451-1458, October 1998.
- [5] Y. Blankenship, P. Sartori, B. Classon, and K. Baum, "Link Error Prediction Methods for Multicarrier Systems", *IEEE 60th Vehicular Technology Conference*, Sep. 2004, Los Angeles, USA.
- [6] A. Pollok, W. Cowley, and N. Letzepis, "Symbol-wise beamforming for MIMO-OFDM transceivers in the presence of co-channel interference and spatial correlation", *IEEE Transactions on Wireless Communications*, Vol.8, Issue 12, pp. 5755-5760, December 2009.
- [7] J. Wang, *et. al.*, "Beamforming Codebook Design and Performance Evaluation for 60 GHz Wideband WPANs", *IEEE 70th Vehicular Technology Conference*, 20-23 Sept. 2009, Anchorage, AK, USA.
- [8] IEEE 802.15 Working Group, IEEE 802.15-08-0355-00-003c, May 2008.